September 4, 2001

Absolute Flux Measurement – Monte Carlo Comparison

Fall 2000 Test Run

G. Mitchell

A measurement of the absolute flux of the neutron beam of MLNSC Flight Path 11a was made in Fall 2000. Detailed comparison of the data to Monte Carlo calculations for the transport of neutrons down the guide indicates good agreement between the measured shape of the energy spectrum and LANSCE calculations for a decoupled liquid hydrogen moderator. For energies from 1 meV to 15 meV, the measured brightness of the partially coupled FP11a moderator is 37% larger than predicted for a decoupled moderator, with large uncertainty due to lack of knowledge of attenuating materials in the flight path. Based on the results of the measurements, with 200 μA proton current the peak flux on FP12 is estimated to be 8×10^7 neutrons/ms/pulse at 8 meV, and the total gamma event rate for NPDGamma on FP12 from 1.5 to 15 meV is estimated to be 1.1×10^8/pulse. This estimated FP12 flux is sufficient for NPDGamma.

Introduction

This is the second and final note documenting a Fall 2000 measurement and analysis of the neutron flux on Flight Path 11a (FP11a) at the Manuel Lujan Jr. Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE). The previous note [1] describes in detail the experimental setup and presents the data. This note compares

Monte Carlo calculations to the measurement on FP11a, and then makes predictions for FP12, which is currently under construction. NPDGamma will use FP12. A source repetition rate of 20 Hz is assumed throughout this note.

A Monte Carlo code [2] was modified to include the moderator brightness for a decoupled liquid hydrogen moderator, as parametrized in [3]. The code was run to simulate the data presented in [1]. The Monte Carlo results and the measurements are in good agreement for the shape of the energy dependence when this moderator brightness is used and appropriate corrections are made to the data. This lends credibility to predictions for the cold neutron flux on FP12. FP12 will view an upper tier, partially coupled liquid hydrogen moderator. The performance of this moderator has never been measured.

The primary data discussed in this note (Table 2, Figs. 4-5) were obtained 11:45 AM to 12:30 PM, September 5th, 2000. The beam profile measurements were taken between 2 PM and 5 PM on the same day.

Beam Profile

With the collimation used for this flux measurement, the beam profile as viewed by the detector was roughly square and flat in intensity. For the four energies used in measuring the beam profile, Monte Carlo profiles are shown in Fig. 1. The Monte Carlo, which included the collimation and geometry of the experimental setup, reproduces the measured shape of the beam.

The full-width at half maximum (FWHM) can be calculated for the beam from these Monte Carlo profiles, and from profiles at other energies. Comparing a curve for Monte Carlo FWHM versus neutron energy to the simple expectation that FWHM $= 8.45/\sqrt{\mathrm{E}}$ (from approximation of the collimation as a point source and using a maximum $v_\perp =$ 7 m/s) and to the measured FWHM's shows good agreement (Fig. 2).

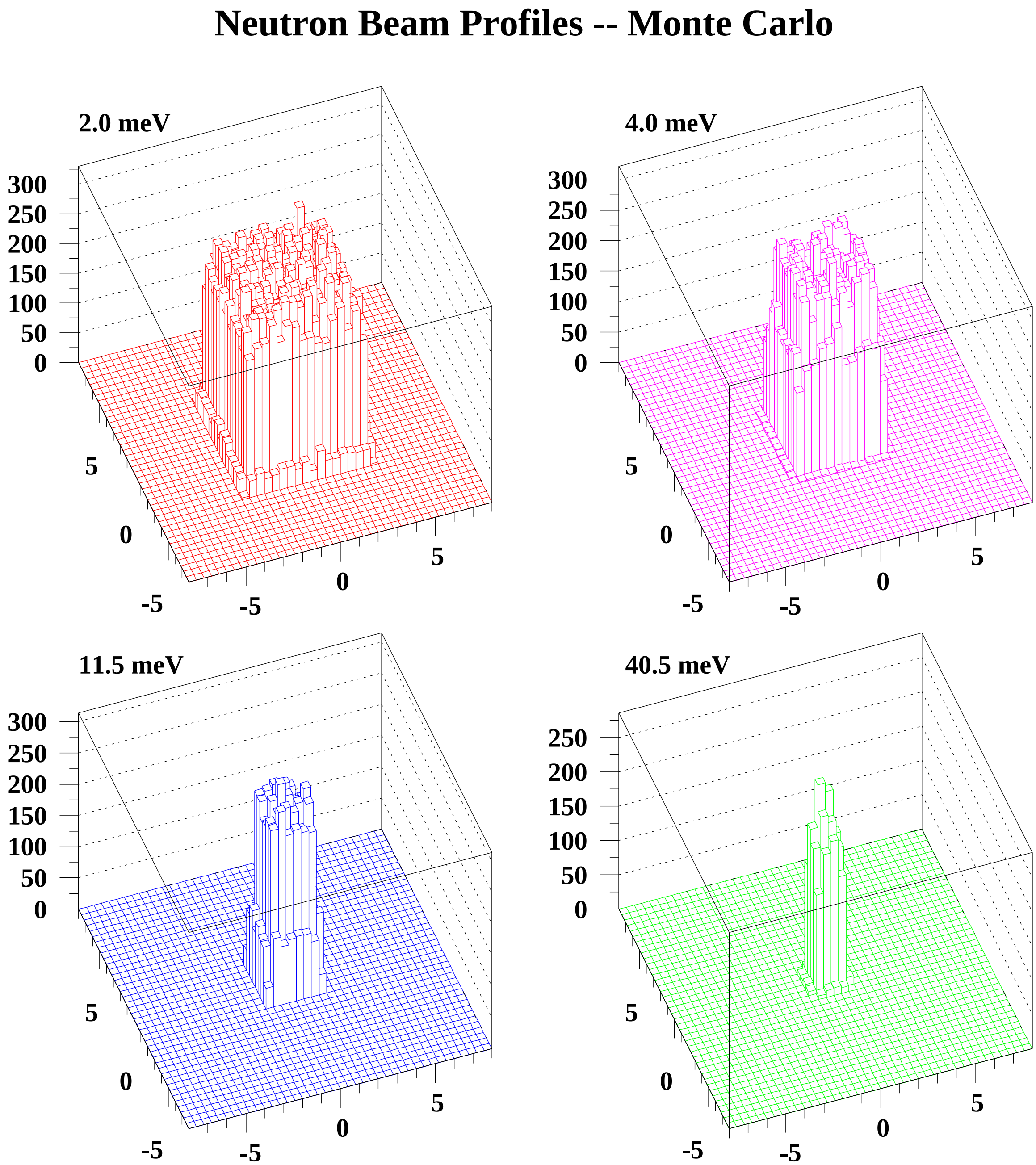

Figure 1: Monte Carlo generated beam profiles for four neutron energies. The x and y axes are in cm, the z axis is neutron counts (arbitrary scale). The point x = y = 0 is the center of the beamline. The profiles are at 2.8 m from the end of the neutron guide, which was the location of the detector. The Monte Carlo included the collimation at the end of the neutron guide.

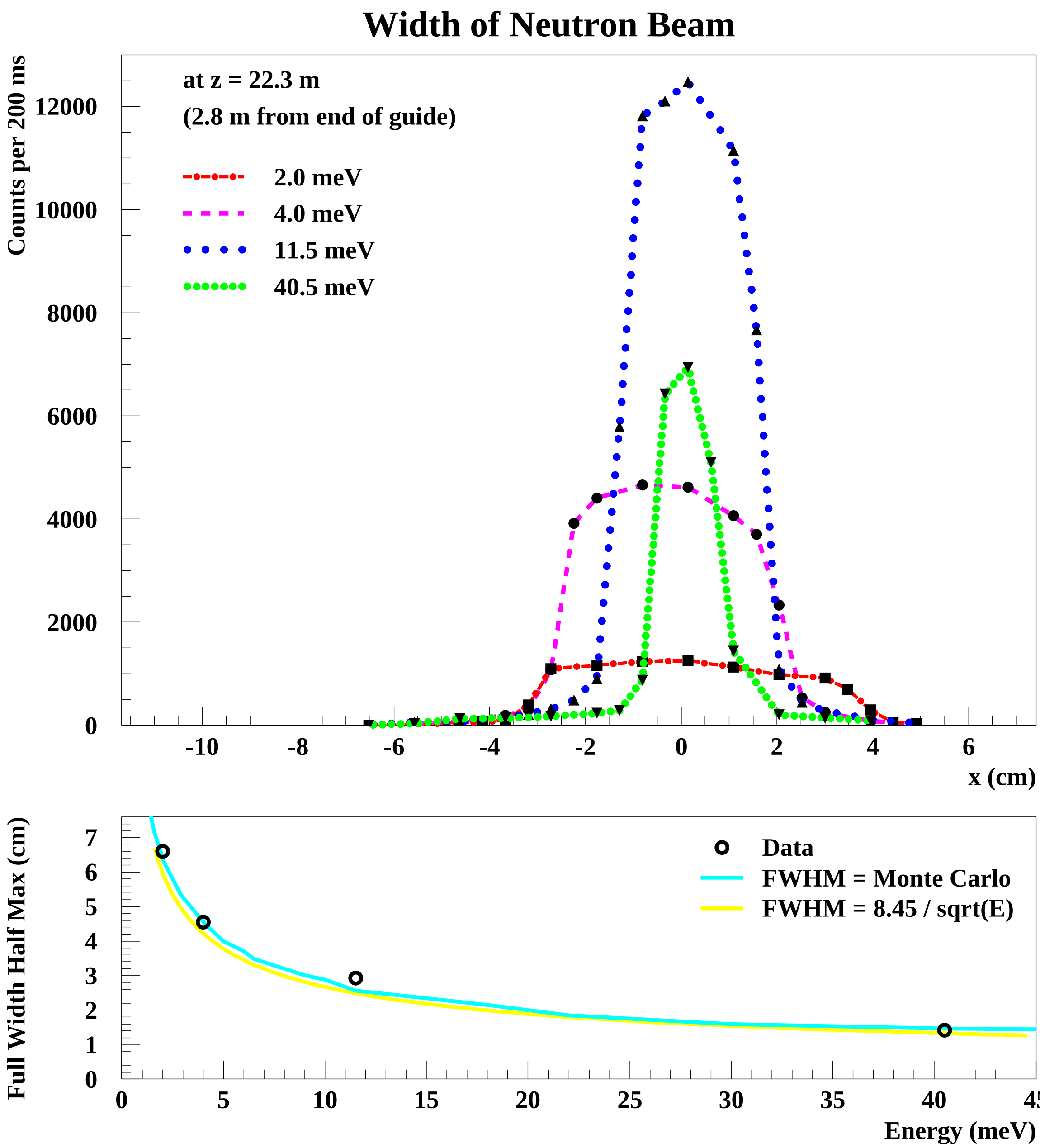

Figure 2: The upper portion of the figure shows the measured profile of the collimated neutron beam at four energies. The lower portion compares the energy dependence of measured FWHM values to a simple geometric prediction, FWHM $= 8.45/\sqrt{\mathrm{E}}$, and to Monte Carlo calculations.

Given its 19 m length, the $n = 1$, ^{58}Ni-coated neutron guide on FP11a makes it possible for cold neutrons to be reflected several times. Experimentally there is no way to know the exact path of a given detected neutron, but from the Monte Carlo it is apparent that for neutrons with E $<$ 40 meV, more than half of the neutrons seen in the profile measurements were reflected at least once. This is shown in Fig. 3. However, with the detector on the z axis (the center of the beamline) as it was for much of this measurement, and with the collimation used for the flux measurement in place, according to the Monte Carlo virtually all of the counts that were seen were not reflected by the guide. Thus the remainder of this note discusses a measurement that was essentially direct viewing of the moderator.

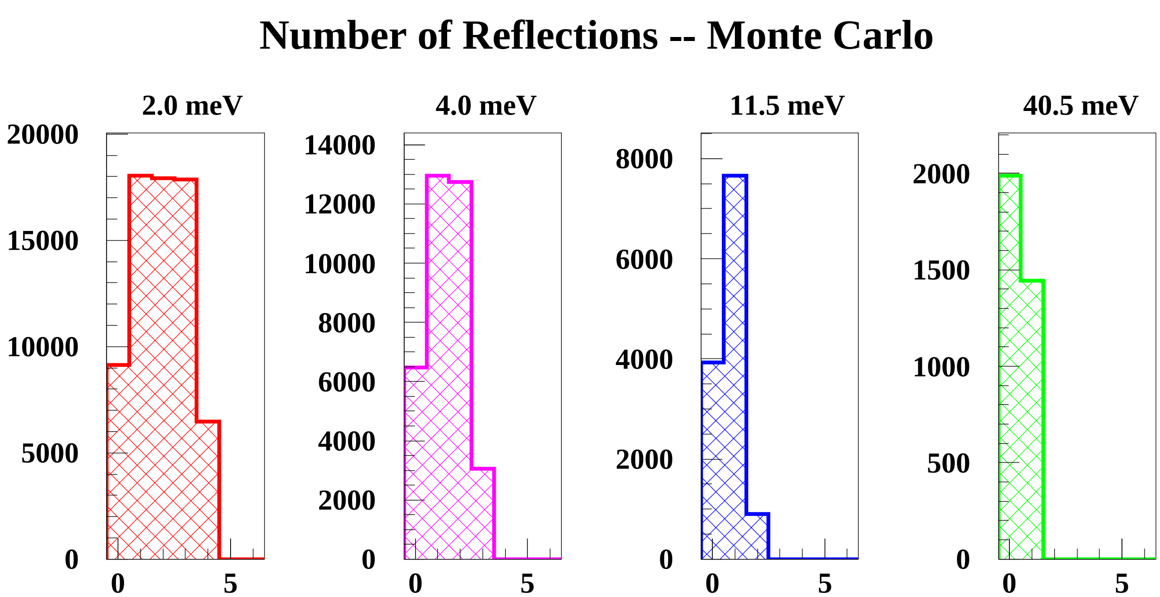

Figure 3: Number of reflections for neutrons travelling down the guide and through the collimation. The x axis of each plot is the number of reflections, the y axis is neutron counts. The events in this figure are the same as those used to create Fig. 1.

Moderator Brightness

The moderator viewed by FP11a is a partially coupled liquid hydrogen (LH_2) moderator. The best available prediction for the brightness of FP11a is a fit provided in [3] for a decoupled LH_2 moderator. This fit should be a low estimate of the brightness, since the partial coupling will enhance the flux at the meV energies of interest here. Another fit in the same reference predicts brightness at 4 meV of five times greater for a fully coupled LH_2 moderator. This factor of five difference between fully coupled and uncoupled moderators gives some estimate of the possible variation in brightness due to the particular geometry and materials surrounding the moderator.

A calculation in Ref. [4] for the FP11a as-built partially coupled moderator predicts, for neutron energies less than 5 meV, a brightness of $0.44 \pm 0.8\% \times 10^9$ $n/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}/\mu\mathrm{A}$. Integrating the fit in Ref. [3] from 1 to 5 meV and estimating the average brightness from 0 to 1 meV to be half that at 1 meV, the brightness from the decoupled moderator fit for energies less than 5 meV is 0.285×10^9 $n/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}/\mu\mathrm{A}$. Thus, based on Ref. [4], a normalization of $0.44/0.285 = 1.54$ is expected when comparing the FP11a measured data to the fit in Ref. [3].

The Ref. [3] brightness curve was used in the Monte Carlo calculations. It was evaluated at energies of interest for this flux measurement, and the results are presented in Table 1. The Monte Carlo results can then be normalized to the data and the normalization factor, presumably greater than unity but less than five, can be applied to this fit for a decoupled moderator to approximate the brightness of the partially coupled FP11a moderator. The expected value for this normalization factor is 1.54.

energy	brightness
1.3	53.36
1.6	59.62
2.1	66.60
2.9	71.08
4.1	70.24
6.5	61.82
11.5	41.42
15.3	29.10
40.5	5.11
161.9	1.33
647.7	0.37

Table 1: Calculated moderator brightness (10^6 neutrons/cm^2/s/sr/meV/μA) , versus neutron energy (meV), from [3], for a decoupled LH_2 moderator. The fit that yielded these values is used in the Monte Carlo. FP11a views a partially coupled moderator and based on Ref. [4], the brightness is expected to be 1.54 times the numbers in this table. FP12 brightness is expected to be 1.5 times the FP11a brightness [4].

Flight Path 11a Flux

The Monte Carlo can be used to calculate an expected number of counts seen in the detector, and a normalization can be determined between the brightness fit and the effective measured result. First the Monte Carlo results are adjusted for attenuation of the neutron beam due to: aluminum windows in the beamline (assume 2 cm, $\approx$ 20% at 10 meV); air between the end of the guide and the detector (2.8 m of 0.8 atm air, $\approx$ 10% at 10 meV); and black polyester tape covering the ^{6}Li detector (0.037 cm, $\approx$ 4% at meV energies). Also, a correction for the efficiency of the ^{6}Li detector is included. This correction is only significant for the three highest energy points (0.40 for 648 meV, 0.64 for 162 meV, and 0.87 for 40.5 meV). The wraparound neutrons (low energy neutrons from the previous 20 Hz pulse which add to the high energy counts) are not accounted for, but are an effect of less than 2%. The corrections for attenuation and efficiency are based on calculations using neutron cross-sections versus energy obtained at [5]. Detector dead time was insignificant for the rates in this measurement.

Monte Carlo results for neutron counts per meV are shown in Table 2. The Experiment column is counts/meV from Ref. [1]. The Raw MC column is counts/meV from the Monte Carlo, using the decoupled LH_2 moderator brightness fit. The Adjusted (Adj.) MC column is counts/meV, adjusting the Raw column for attenuation due to aluminum windows, air, tape, and for ^{6}Li detector efficiency. The final column presents the ratio of the Experiment column to the Adjusted MC column.

Table 2. Neutron counts/meV/pulse from experiment and Monte Carlo, for collimated neutron beam on FP11a.

E (meV)	Experiment	Raw MC	Adj. MC	Ratio: Expt/Adj. MC
647.7	0.44	0.4	0.1	3.74
161.9	1.29	1.3	0.6	2.13
40.5	3.38	5.8	3.6	0.93
15.3	27.12	29.7	20.2	1.34
11.5	38.21	42.1	28.8	1.33
6.5	57.22	66.4	44.0	1.30
4.1	69.99	75.0	48.4	1.45
2.9	72.14	80.1	50.7	1.42
2.1	62.97	72.1	44.8	1.40
1.6	53.54	56.5	34.7	1.54
1.3	41.24	59.8	36.4	1.13

Average ratio, last 8 points (E <= 15.3 meV): 10.92/8 = 1.37

Without the ^{6}Li efficiency, the data and Monte Carlo are compared in Fig. 4, and the energy dependence agreement is good. However, there is a discrepancy between the trend of the Monte Carlo and of the data for the highest energy points when the ^{6}Li efficiency is included. The origin of this discrepancy is not definitively understood. The most likely contribution is that the collimation of Gd foil and borated poly was less effective for neutron energies greater than 40 meV. Another possible cause is uncertainty in the neutron time of flight (tof). The neutron energy was selected by using an oscilloscope to set an electronic gate at a certain tof, and for small tof's there is some uncertainty in the neutron energy. For example, the highest energy point was taken at tof = 2 ms. If instead the true tof was 2.5 ms, then the energy was ~400 meV instead of 648 meV, and the conversion to counts/meV (which uses a factor of tof / 2E) is altered, as is the ^{6}Li detector efficiency. For the high energy points at small tof's, errors of order 0.5 ms can lead to a correction to counts/meV of a factor of 2. The tof uncertainty is a small effect for the low energy points since they occur at larger tof's.

Other possible systematic uncertainties include the composition of the ^{6}Li detector and background counts in the detector. The composition of the detector influences the adjustment for detector efficiency at the higher energy points. Background counts were measured by placing a solid borated poly plug into the collimation assembly (see details in [1]). However, this measurement was only made for the tof corresponding to 4 meV neutrons, and backgrounds could have been larger for the tof's corresponding to higher energy neutrons.

For the eight lowest energy points of the measurement, 1.3 meV $\leq$ E $\leq$ 15.3 meV, the shape of the Monte Carlo agrees with the shape of the data. Figure 5 shows the data, the Monte Carlo, and a normalized Monte Carlo curve. The average of the ratio of Experiment to Adjusted Monte Carlo is used to normalize the moderator fit upwards to account for the partial coupling. Since the NPDGamma experiment is primarily interested in neutron energies less than 15 meV, only the last eight energy points (those less than and including 15.3 meV) are used in finding this average ratio. The conclusion is that the brightness fit underestimates the FP11a brightness by 37%. This result may be optimistic since most likely there is not more than 2 cm of aluminum in the beamline from various windows. Other unknowns are possible misalignment of the guide and guide imperfections, which both would cause less than ideal neutron transmission. Effects of this nature are not accounted for here. The normalization value 1.37 compares well to the predicted value of 1.54, differing by 11%.

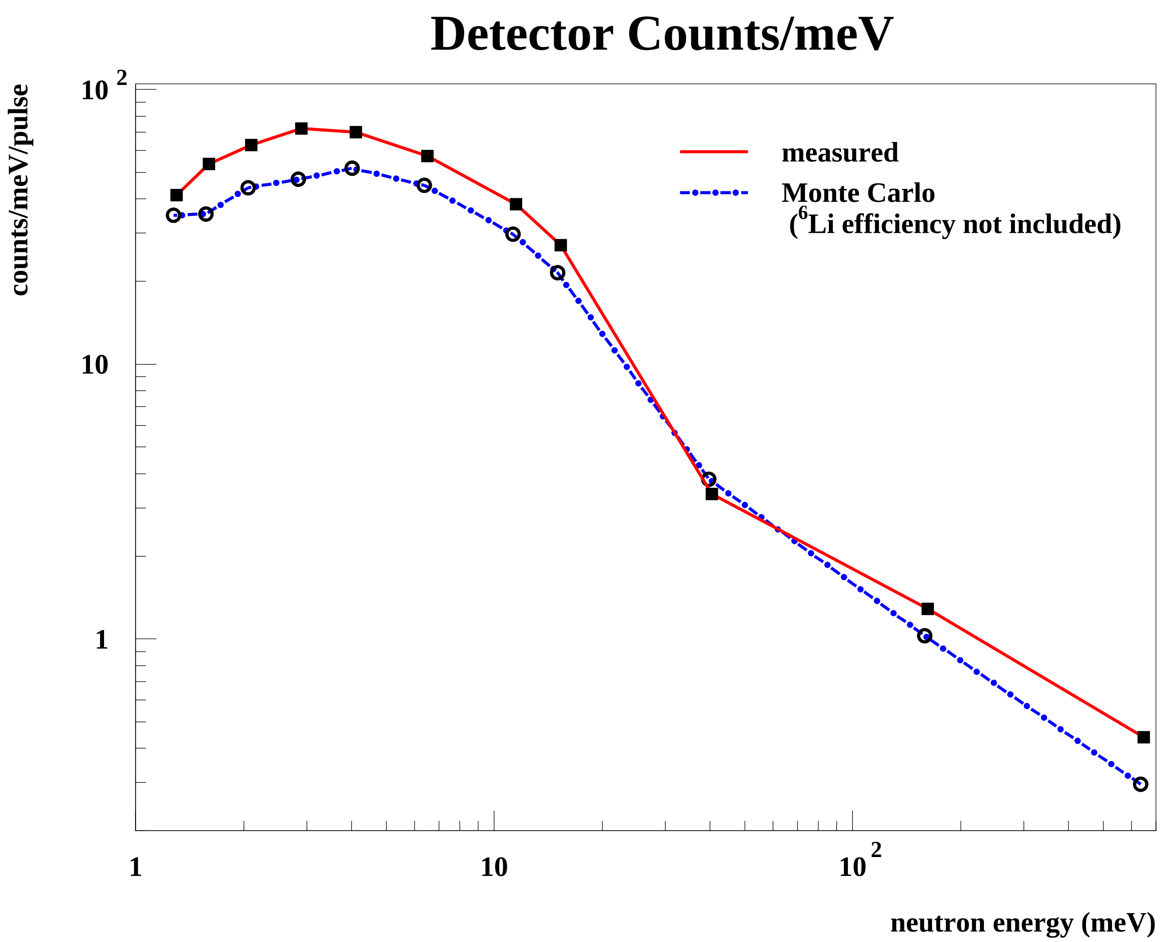

Figure 4: Comparison of data to Monte Carlo. Data (boxes) are from [1]. The open circles indicate Monte Carlo points and they have been shifted slightly for clarity. The error bars on the Monte Carlo points are statistical only. The Monte Carlo includes effects of attenuation due to: 2 cm of Al windows in the beam line; 2.8 m of 0.8 atm air in the cave between the end of the guide and the detector; and 0.037 cm of black polyester tape. This figure does not include the ^{6}Li detector efficiency, which significantly lowers the three highest energy Monte Carlo data points.

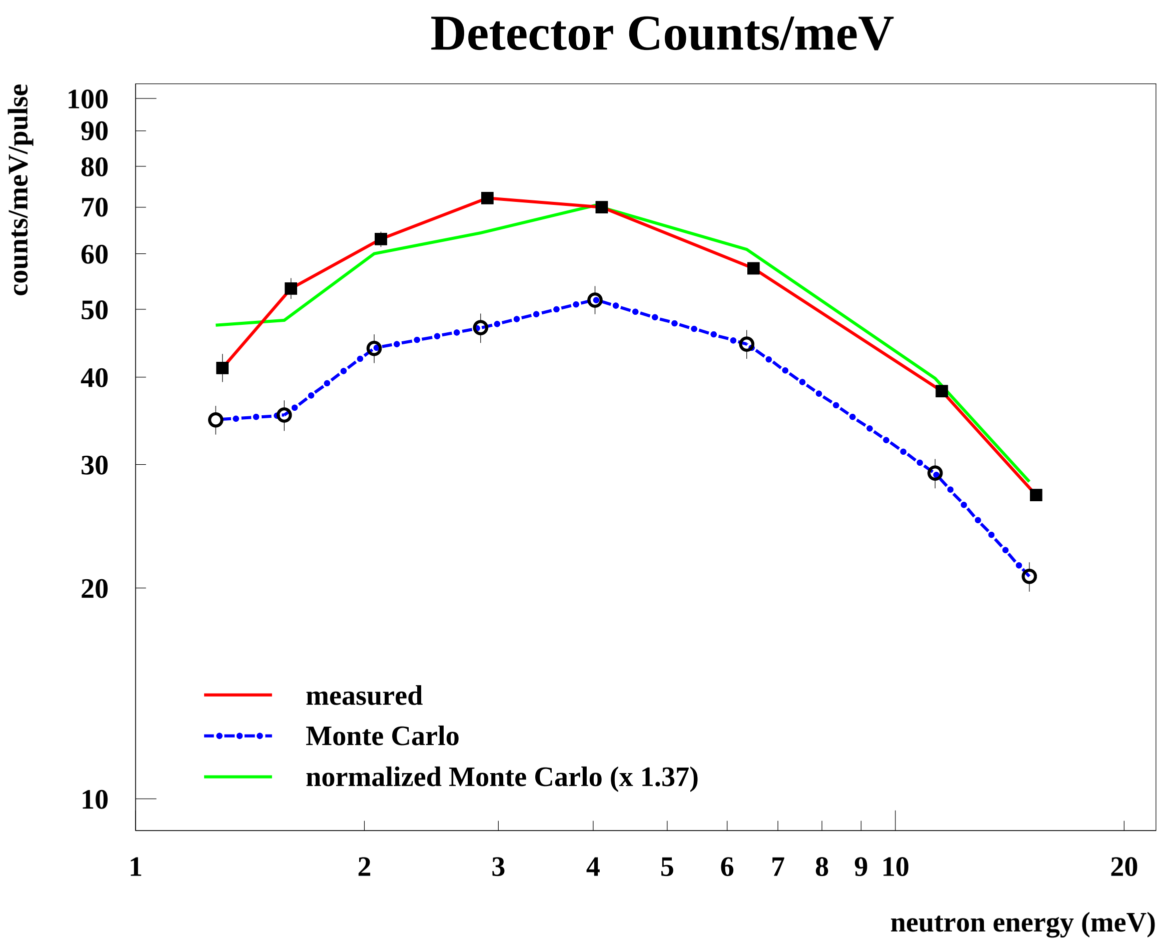

Figure 5: Comparison of data to Monte Carlo. Data (boxes) are the eight lowest energy points from [1]. The open circles indicate Monte Carlo points and they have been shifted slightly for clarity. The Monte Carlo includes effects of attenuation due to: 2 cm of Al windows in the beam line; 2.8 m of 0.8 atm air in the cave between the end of the guide and the detector; and 0.037 cm of black polyester tape. Also included is the efficiency for the ^{6}Li detector, which is greater than 96% for all points shown here. The green curve shows the Monte Carlo points adjusted by a factor of 1.37, which is the normalization which provides the best agreement with the data. This normalization is equivalent to the statement that the LH_2 moderator viewed by FP11a has 37% more flux for these energies than a decoupled moderator would provide.

Prediction for Flight Path 12 Flux

Two quantities in particular are of interest for FP12 and the NPDGamma experiment: the peak flux (at ~8 meV) and the total flux from 1.5 to 15 meV. The peak flux is a useful number for estimating maximum currents that will be seen in beam monitors and the detectors. The total flux is useful for calculating the total event rate and thus for making and assessing run time estimates.

To predict the neutron flux on FP12, the Monte Carlo for FP11a was altered to account for the differences shown in Table 3.

	FP11a	FP12
guide reflectivity order	$n = 1$	$n = 3$
guide size	6×6 cm	9.5×9.5 cm
distance, moderator to guide	1 m	1.37 m
guide length	19 m	16.61 m
distance, end of guide to ...	detector: 2.8 m	target: 1.0 m
proton current	90 μA	200 μA

Table 3: Differences between Monte Carlo for FP11a (flux measurement, Fall 2000) and FP12 (NPDGamma).

The reflectivity of the $n = 1$, ^{58}Ni-coated FP11a guide was modeled as 99% for neutrons with perpendicular velocity $v_\perp$ with respect to the guide surface of less than 7.5 m/s. For the $n = 3$ FP12 guide the reflectivity was modeled as: 99% for $v_\perp < 7.5$ m/s; linearly decreasing from 99% to 81% for $v_\perp$ from 7.5 m/s to 22.5 m/s; and zero for $v_\perp > 22.5$ m/s. For both flight paths, the Monte Carlo moderator size was 12.5×12.5 cm.

The Monte Carlo simulated the trajectories of five million neutrons at each of several energies (primarily the same energies as in the flux measurement on FP11a). The output of a run of the Monte Carlo for FP12, with the tof calculated for the LH_2 target at 1 m from the end of the neutron guide, is given in Table 4. The total flux is calculated by summing the values in the energy range and interpolating at the endpoints.

```
Table 4.  Uncollimated FP12 Monte Carlo neutron flux out of the guide.

Using decoupled LH2 moderator brightness, adjusted for:
FP11a measurement, FP12 vs. FP11a, aluminum windows
(factor of 1.37 x 1.5 x 0.8 = 1.64)

Energy in meV, tof in ms, n/meV/pulse and n/ms/pulse are x10^6
Source units: x10^6 neutrons/sr/meV/proton pulse
```

meV	tof	n/meV/pulse	n/ms/pulse	source
647.70	1.71	0.02	16.51	955.3
161.90	3.41	0.14	13.05	3420.6
40.50	6.82	1.70	20.21	13085.6
15.30	11.09	23.22	64.05	74579.3
11.50	12.80	42.45	76.30	106146.6
8.00	15.34	76.64	79.93	142072.8
6.50	17.02	100.32	76.63	158420.9
4.10	21.43	160.43	61.39	179992.9
2.90	25.48	205.16	46.70	182141.3
2.10	29.94	236.63	33.19	170652.1
1.60	34.31	248.96	23.22	152777.6
1.30	38.06	250.34	17.10	136745.0

```
total flux from 1.50 meV to 15.00 meV : 13.1 x 10^8 neutrons/pulse
```

The results include adjustments for two significant factors, one for the underestimate of the FP11a flux by the decoupled moderator fit, and one for the increased brightness of FP12 as compared to FP11a. The first factor, as discussed above, is 1.37. For the second factor, according to [4], the brightness of FP12 will be 50% larger than FP11a for cold neutrons. This is attributable to the geometry of the flight paths: FP11a has a flux-trap moderator while FP12 has a back-scattering geometry. Thus an additional factor of 1.5 is used.

In calculating the expected number of neutrons emerging from the end of the FP12 guide the attenuation due to Al windows must also be included. This was accounted for as a scale factor of 0.8, based on the assumption of 2 cm total thickness of aluminum in the flight path, and using the neutron cross-section value at 10 meV. The source column in Table 4 includes this factor.

For calculating the number of neutrons incident on the NPDGamma target, attenuation due to air in the cave must be included. Also, for calculating the number of neutron capture events, the ^{3}He spin polarizer has an average transmission coefficient of 0.2 for neutron energies of 1.5 to 15 meV [6], and the solid angle coverage of the detector is roughly $\frac{2}{3}$.

Assimilating all of the necessary factors together, using scaling factors independent of neutron energy, a prediction for the total flux is made as follows:

- Monte Carlo flux out of the end of the FP12 guide, partially coupled LH_2 moderator, for 1.5 meV $\leq$ E $\leq$ 15 meV: 13.1×10^8 neutrons/pulse
- Attenuation due to 1 m of air: 0.95
- Transmission of ^{3}He polarizer: 0.2
- Capture fraction in LH_2 NPDGamma target: 0.65
- Solid angle coverage of CsI(Tl) γ detectors: 0.67

which together yield a total gamma event rate for NPDGamma of 1.1×10^8 per pulse. This is sufficient for making a measurement of A_γ with an error of 10^{-4} per pulse ($\sigma = 1/\sqrt{N}$), necessary for NPDGamma run time of order one year. Error of 10^{-4} per pulse on A_γ is the NPDGamma proposal target value.

According to the Monte Carlo, the peak flux will occur at 8 meV, and it will be:

$$8 \times 10^7 \text{ neutrons/ms/pulse.}$$

This is the peak flux out of the end of the guide and estimates of flux at different locations in the cave will require further attenuation factors for elements in the beamline. The NPDGamma proposal presents figures showing the peak flux at 0.75 meV [7]. These figures are incorrect for the current design of FP12. The FP12 peak flux (per ms per pulse) will occur at 8 meV, as shown in Fig. 6.

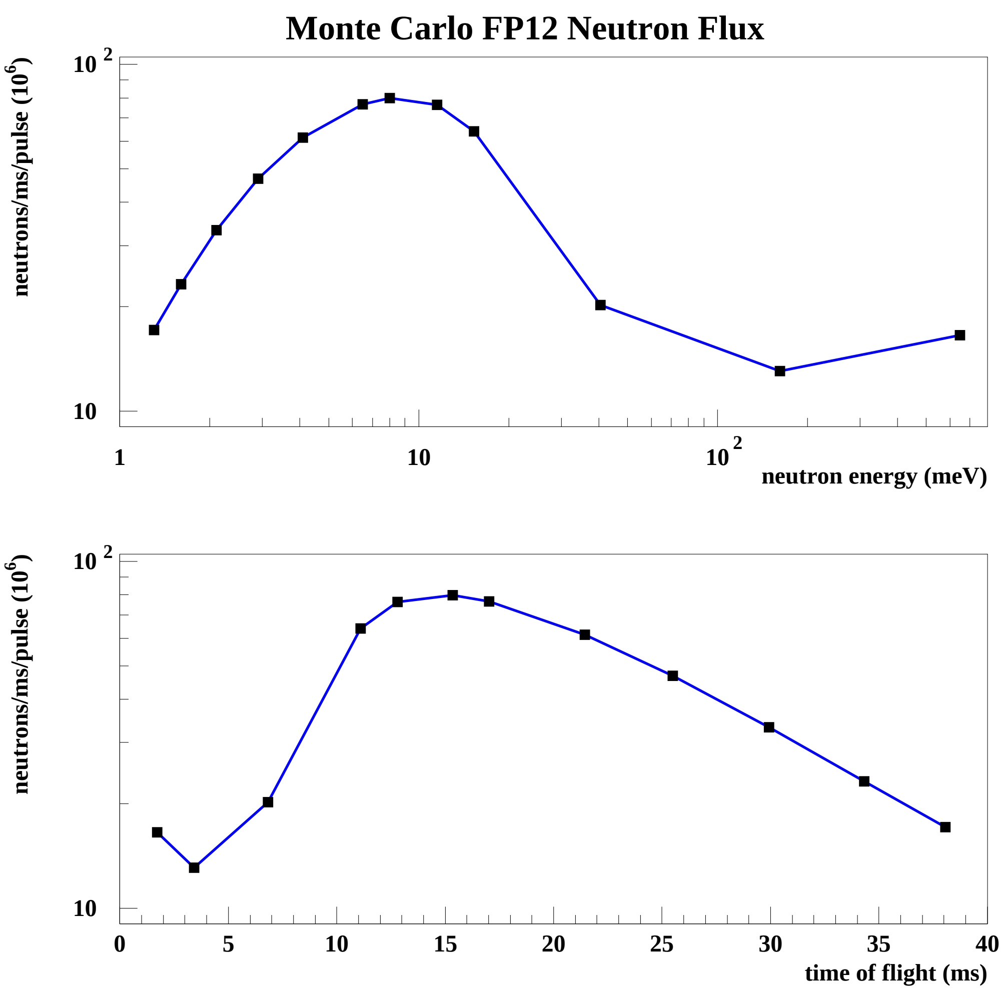

Figure 6: Monte Carlo results for neutron flux out of the end of the FP12 guide. The time of flight is for a z location 1 m past the end of the guide, which will be the location of the NPDGamma target. Data used to make this figure are in Table 4.

Summary

Neutron beam profiles for the collimated beam on FP11a are reproduced well by the Monte Carlo. The neutron flux measured on FP11a agrees with Monte Carlo calculations in its shape versus energy for E$\leq$15 meV. For these energies the effective measured brightness is 37% higher than predicted for a decoupled LH_2 moderator. A large uncertainty in this number arises from lack of knowledge of material in the beamline, such as aluminum windows. The flux estimates here are conservative in their values for beam attenuation, while the value of 200 μA for proton current incident on the spallation source may be optimistic. The peak flux out of the end of the guide on FP12 for NPDGamma is predicted to be 8×10^7 neutrons/ms/pulse at 8 meV. For neutrons with energy from 1.5 meV to 15 meV, the NPDGamma predicted gamma event rate is 1.1×10^8/pulse. This estimate of flux for the new FP12 indicates it will be sufficient for NPDGamma.

References

[1] Mitchell, G., 'Absolute Flux Measurement–Preliminary Summary,' NPDGamma Technical Note, December 2000.

Available at: http://p23.lanl.gov/len/npdg/technotes/flux_summary.pdf

[2] Original Monte Carlo code written by Todd Smith (LANL P-23).

The code and some minimal documentation are available at:

http://p23.lanl.gov/len/npdg/technotes/monte_carlo/

[3] Ferguson, P. D., Russell, G. J., and Pitcher, E. J., 'Reference Moderator Calculated Performance for the LANSCE Upgrade Project,' ICANS-XIII (1995).

The proceedings of this conference were published by the Paul Scherrer Institut as PSI Report 95-02.

[4] Muhrer, G., Ferguson, P. D., Russell, G. J., and Pitcher, E. J., 'As-Built Monte Carlo Model of the Lujan Target System and Comparison of its Neutronic Performance to a Physics Model,' LANL Report LA-UR-00-6078 (2000).

This reference gives the following numbers in its 'as-built model 1' column in Table 2, for E<5 meV: FP11a, 0.44 $\times 10^9$ neutrons/cm^2/s/sr/μA; and FP12, 0.67$\times 10^9$ neutrons/cm^2/s/sr/μA.

[5] ENDF-VI neutron cross-sections were obtained in table format from:

http://t2.lanl.gov/data/ndviewer.html

[6] NPDGamma proposal, page 27.

Available at: http://p23.lanl.gov/len/npdg/proposal/proposal.html

[7] NPDGamma proposal, page 18 and page 20.